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ARTIFICIAL INITIATION OF THE SUPERSONIC TRANSITION

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ARTIFICIAL INITIATION OF SUPERSONIC TRANSITION

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ABSTRACT. Following a comparison of the criteria proposed by various authors for defining the height of roughnesses necessary to initiate transition in supersonic flow, the results obtained in the S-2 wind tunnel of the Modane Center during a preliminary study for industrial tests are described.

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A choice of the criteria allowing a definition of the location and of the height of the critical roughnesses initiating transition without giving any additional drag is proposed. An examination of this additive drag leads, in the case of industrial tests, to an appropriation of the artificial initiation of transition as a function of the precision required in the determination of the cruise-flight drag from wind-tunnel tests.

I. Introduction

To be able to estimate the in-flight drag of a plane, one must know the exact amount of resistance contributed by friction to the total drag measured in wind-tunnel experiments. Though the artificial initiation of the transition enables us to control the location of the transition line, special care must be used during the preliminary search for a critical roughness height which causes the initiation of the transition and yet does not bring any additive drag by its presence.

In subsonic and transonic flow, it is possible to adopt relatively simple criteria [9]. Thus R_{hh} , the roughness Reynolds number based on the height h and on the conditions existing at the top of the roughness, is a frequently-used criterion. Many authors [3] agree on a value of 500-600 for R_{hh} independent of the Mach number, at least up to Mach 1.

In supersonic flow, the process of initiating the transition by three-dimensional roughnesses becomes more complex [6]: it requires the intervention of a contamination zone downstream from the roughness. This new parameter explains the diversity of criteria used by different authors [3,4,6,7,8]. The important variation of these criteria with the Mach number no longer allows us to keep constant the two following parameters: location and height of the roughness when tests are made with constant Reynolds number or constant generating pressure

*Numbers in the margin indicate pagination in the foreign text.

in a wide range of Mach numbers. Indeed, in such conditions the additional drag created by the roughnesses themselves would be noticeable.

II. Type of Roughnesses

The technique of artificially starting the transition used for the tests described in section VIII consists of placing glass pearls in one row at equal intervals on the model (Fig. 1).

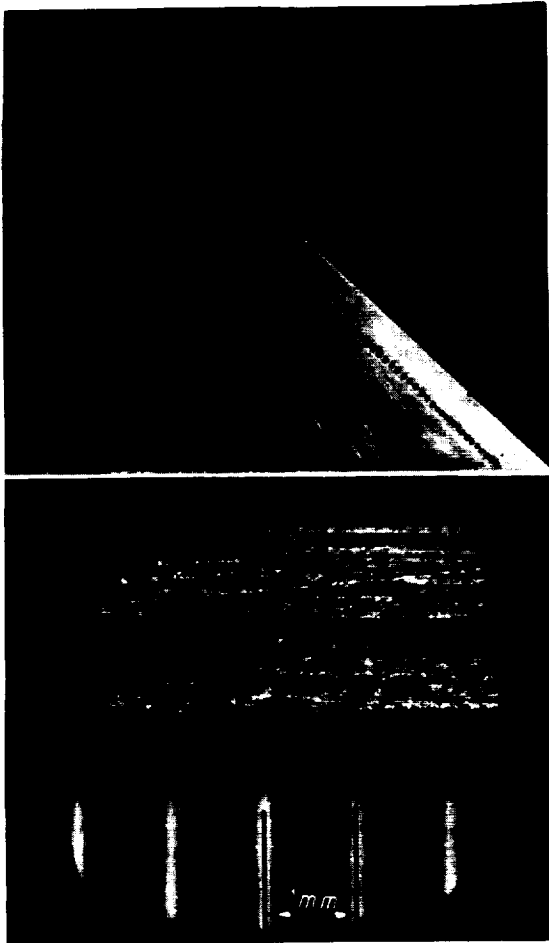


Fig. 1. Spherical Roughnesses $h = 0.14 \text{ mm}$.

Four reasons have motivated the choice of this process:

1. Elimination of two parameters which occur in the process of spreading carborundum grains in a well-delimited zone: width of the zone and density of the grains.
2. More accurate calibration of the glass pearls because of their very shape.
3. Possibility of reproducing the roughnesses from one test to another.
4. Comparison with the tests done with the same process by several authors [3,4,6,7,8].

The application of this technique includes the following operations: lay a film of glue about .01 mm thick on which calibrated glass pearls are positioned at regular intervals, then wrap the particles by spraying them with a diluted solution of glue which preserves their spherical shape.

The making of ultra-thin supports, all equipped with calibrated pearls placed at constant distance from each other, is in progress. The possibility of reproduction will thus be assured. The time for preparing a model will be reduced to that necessary for the simple gluing of prefabricated strips. Moreover, it will be possible

to regularly space pearls of diameter smaller than 0.2 mm, an unthinkable possibility during their manual application for industrial tests.

III. Location of the Roughnesses

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The average friction coefficient for a flat plate of length l on which the transition is located at a distance x from the front edge is [1]:

$$C_F(x) = \frac{1,328}{R_{x^{1/2}}} f_L \frac{x}{l} \left[1 + 0,01685 \left(\frac{l}{f_L} \right)^{4/5} R_{x^{1/2}} \left(\frac{l}{x} - 1 \right) \right]^{5/8}$$

The Reynolds number $R_X = x \frac{U_e}{\nu_e}$, with the subscript e standing for the edge of the boundary layer. The functions f_L , f_T are dependent on M_e and T_e .

This formula is based on the junction in x of the thicknesses δ_2 of momentum of the laminar and turbulent boundary layers.

By examining the curve $C_F(x) = F(x)$ one finds a value x^* defined by the relationship:

$$R_{x^*} = 27,130 \left(\frac{l}{f_L} \right)^{3/5}$$

under which the coefficient of friction is greater than the one for the totally-turbulent flat plate. This is equivalent to saying that x^* constitutes a limit value under which the laminar part of the flat plate has an average coefficient of friction greater than the one it would have if it were turbulent, or that the turbulent boundary layer has a fictitious origin upstream from the leading edge.

It does not seem suitable to put the roughness line upstream from the abscissa x^* . According to the hypothesis of an athermanous flat plate, the Reynolds number R_{X^*} is a function of M and of the generating temperature T_i . The curve $R_{X^*} = F(M_e)$ corresponding to a constant temperature $T_i = 293^\circ \text{ K}$ is shown in Fig. 2.

Under such conditions, the height of the roughness h will always be smaller than the height δ of the laminar boundary layer as Evans suggested [2]. Indeed, in Fig. 2 we find the values R_X for which $h = \delta$:

$$R_{h,\delta} = h \frac{U_e}{\nu_e} = R_\delta = 0,664 f_L R_{x^{1/2}} \frac{\delta}{f_L}$$

The values found are much smaller than R_{X^*} , whether the Reynolds number R_{he} is calculated from the Braslow criterion [3] -- R_{he} from 600 to 900 according to the value of M -- or from the Van Driest and Blumer criterion [4]:

$$R_{h,\delta} = 42,6 (1 + 0,2 M^2) R_{x^{1/4}}$$

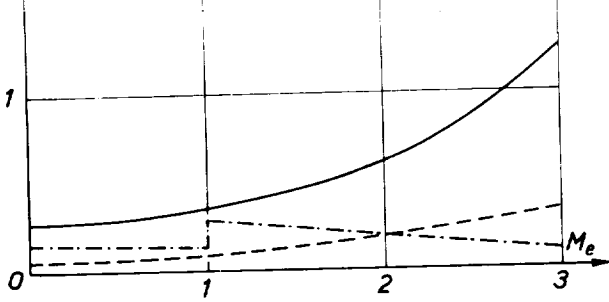


Fig. 2. Location of the Roughnesses.

$$\text{Law } R_{X^*} = 27,130 \left(\frac{f_L}{f_T} \right)^3 \text{ ---}$$

Curves for which $h = \delta$:

from R_{he} Van Dries, Blumer ----

from R_{he} Braslow - - - -

$$\begin{cases} M < 1 & R_{he} = 600 \\ M > 1 & R_{he} = 900 \end{cases}$$

Van Driest and MacCauley [6]. Two swirls issued from the particle expand in a direction parallel to the flow up to a contamination line of abscissa x_c ; from there, a triangular turbulent zone expands at an approximative 7° half-angle.

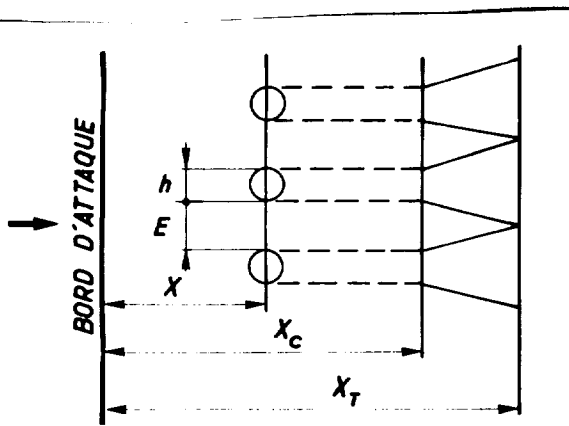


Fig. 3. Initiation of the Transition.

number decreases by increasing R_{hh} . However, there seems to be a limit value of the distance $x_c - x$ from which the increase of R_{hh} remains without effect; this

IV. Spacing of the Roughnesses

In the case of three-dimensional roughnesses, Cowled [5] shows that a 3:1 ratio between the interval E between particles and their height h is necessary for each particle to keep its characteristics as if it were alone.

For smaller intervals an interaction between particles appears. It is then necessary, as Braslow shows [3], to introduce a correction into the criteria of the transition initiation to permit comparison with the criteria proposed by various authors.

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V. Location of the Transition Line

The process of initiating the transition by spherical particles located on an x abscissa is divided into two steps shown by

The existence of several roughnesses helps to make the whole surface turbulent from the line where the turbulent triangular zones intersect. This line, located on abscissa x_T , defines a distance $x_T - x_c$ function of the distance E between two roughnesses (Fig. 3).

The distance of contamination $x_c - x$, independent of E , varies roughly as the square of the Mach number [4]. Moreover, Braslow [3] shows that it can be related to the roughness Reynolds number $R_{hh} = h(U_k/V_k)$ based on the conditions at the top of the roughness: the contamination distance can be further reduced as the Mach

limit value rapidly grows with the Mach number, especially above Mach 2.

In supersonic flow it is no longer enough in the given conditions to seek the roughness height h which will initiate the transition, but it is now more necessary to define the distance downstream from the roughness at which the contamination is desired. For this reason, beginning at Mach 1.6, the criteria for the transition initiation proposed by various authors differ more as smaller contamination distances are sought [7,8].

VI. Visualization of the Transition Line

The commonly-used method of visualizing the transition is based on the sublimation of a volatile product which disappears in turbulent zones and thus reveals the change in nature of the boundary layer in a distinct, clear-cut way. The visualizing techniques and the recording of their results have already been described [9].

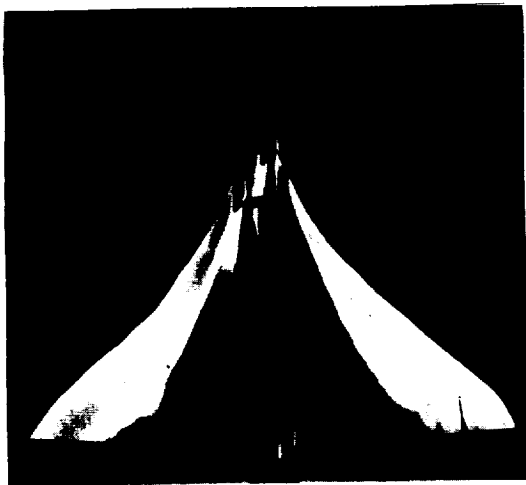


Fig. 4. Natural Transition. S 2 MA. $M_e = 2.34$, $p_i = 0.95$ bar, Comparison Grain.

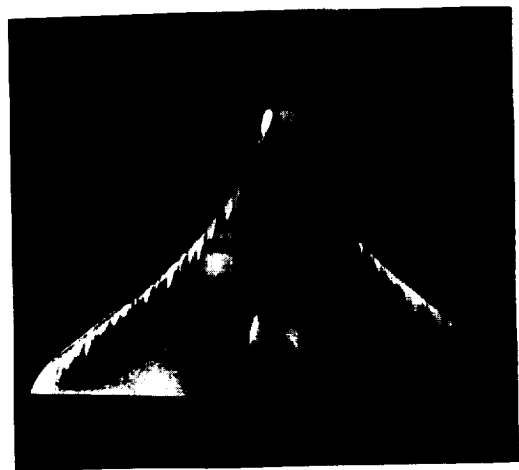


Fig. 5. Artificially-Initiated Transition. S 2 MA. $M_e = 2.34$, $p_i = 0.95$ bar, $x = 8$ mm, $h = 0.14$ mm.

In supersonic flow, the transition zone which spreads downstream from the roughness increases with the Mach number. It becomes more important to know the meaning of the visualized line. In natural transition, comparisons [10] between methods which locate the beginning and the end of the transition zone permit putting the visualized line very close to the middle of this zone. In artificially-initiated transition, the visualizations in supersonic flow distinctly show both the swirls linked to the roughnesses [6] when these are still well individualized and the turbulent triangular zones.

Fig. 4 clearly shows the process of initiating the transition by a single particle deliberately placed in a zone which would normally be laminar in natural transition. Fig. 5 shows the same model in the same test conditions but with a roughness line which allows the initiation of the transition: the fringed aspect downstream from the roughness line shows that the contamination occurs there and that the surface is totally turbulent only after that. For a greater roughness height at the same Mach number the initiation has been brought practically on the roughness line.

By copying the transition line on transparent plastic it is possible to take into account the triangular turbulent zones when computing the average friction coefficient of the surface in question. The partially turbulent structure of the contamination zone is therefore not considered.

VII. Critical Reynolds Roughness Number

Many authors have given criteria for the initiation of the transition based upon the Reynolds roughness number computed from the height h from which the transition can be initiated:

Braslow's nomographs [11] allow the definition of the roughness height h from the distance x , the experimental conditions and the Reynolds number R_{hh} . The value of R_{hh} to be used in subsonic and transonic flow is between 500 and 600. In supersonic flow this value increases and varies between 600 and 900 at Mach 2 [3] according to the distance of contamination.

The formula proposed by Van Driest and Blumer [4]

$$R_{he} = 42.6(1 + 0.2 M_e^2) R_x^{1/4}$$

permits calculating the roughness Reynolds number based on the conditions at the edge of the boundary layer. The location of the transition line is drawn from the approximated formula

$$R_{xT} - R_x \sim 6.8 \cdot 10^4 M_e^2$$

at least for large enough x/h values ($x/h > 200$ for $M_e = 2.7$) below which R_{xT} remains constant, since the transition is fixed by the sides of the roughness and no longer by its extremity [6].

Evans suggested taking a Reynolds number $R_{h/2}$ based on the radius of the particle and on the conditions at half-height of this one and making this number equal to 200, at least up to $M = 2.4$. This constant, combined with the condition of not exceeding the height of the boundary layer, leads to minimal values of x and h and therefore small x/h values.

In order to bring the contamination back on the roughness line in supersonic flow, Smith and Clutter [7] correct the value of 400 obtained in subsonic flow for the Reynolds roughness number R_{hh} by a function of the Mach number M_h

which occurs at the top of the roughness:

For values of $M_h \gg 0.75$, Potter and Whitfield [8] obtain a formula of the same kind:

$$R_{hh} = 400 \cdot \left[\frac{1 + \frac{\gamma - 1}{2} M_h^2}{\frac{\gamma + 1}{2}} \right]^{1.26} M_h$$

C is determined from the condition of the contamination by a law:

In this law x , x_T and the position of the natural transition x_{T0} appear; K is a constant depending on the type of roughness and on the Mach number. For spherical roughnesses placed in a single row on a flat plate, the value of K is indeed incompressible, that of 600 proposed by Klebanoff [12]; at $M_e = 3$ this value becomes equal to 3,000. By taking $C = K$ it is possible to bring the transition back on the roughness line.

For a unit Reynolds number (per meter) $R_0 = 10 \cdot 10^6$ and a generating temperature 293°K chosen for this example, the values x^* of the location of the roughnesses which have been proposed in section V are plotted as a function of the Mach number in Fig. 6. Under the same conditions, the computation of the roughnesses location with Evans' criterion (Fig. 6) reveals values for x markedly more upstream and approximately one half of x^* .

The comparison between the criteria proposed by the various authors is made for a Reynolds number $R_0 = 10 \cdot 10^6$ and at distances x^* which have been obtained earlier. In the application of each criterion, the Reynolds roughness number R_{hh} (Fig. 7) and the height of the roughness (Fig. 8) are computed. For each of these two curves the limit for which $h = \delta$, i.e. where $R_{hh} = R_{he}$, is shown. (2) As a comparison, the values of R_{hh} and of h taken from Evans' criterion are plotted, although they do not correspond to the values of x^* .

Above Mach 2, the Smith and Clutter criterion leads to values of h which are closer to the thickness of the boundary layer δ and equal to it at Mach 3. Since this criterion relies on finding a null contamination distance, the values of h and R_{hh} are noticeably different from those found with other criteria at high Mach numbers.

In the case where the constant K has the value 600 issued from

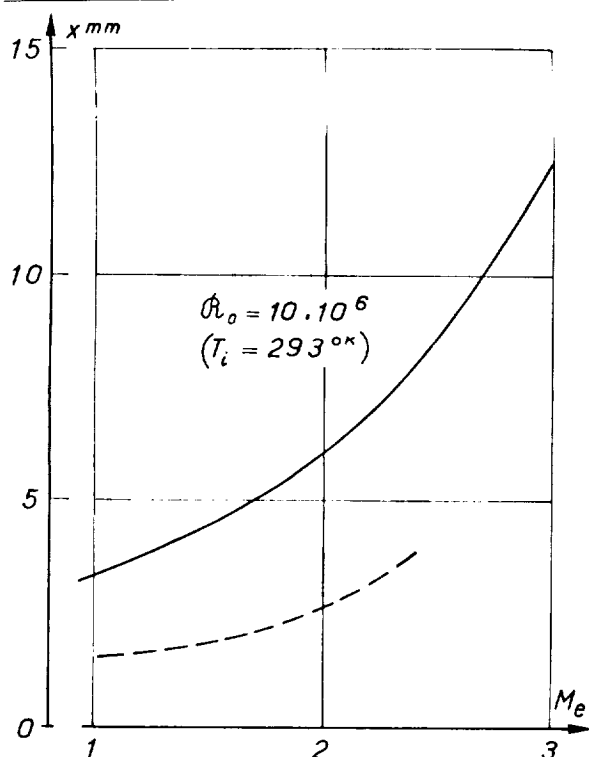


Fig. 6. Location of the Roughnesses.
 — from the law $R_{x^*} = F(M_e)$
 - - - according to Evans: $h = \delta$,
 $R_{h/2} = 200$

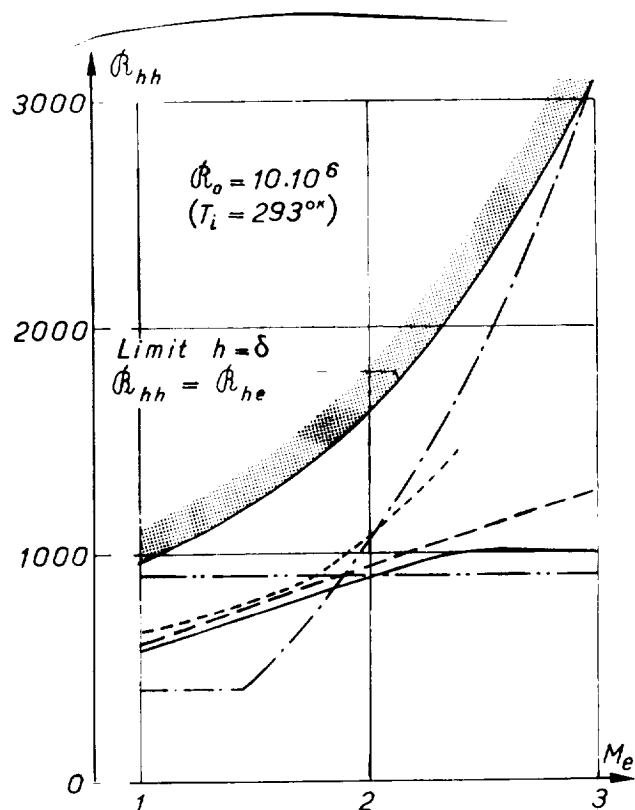


Fig. 7. Reynolds Roughness Number R_{hh} , from:
 Van Driest and Blumer —
 Smith and Clutter - - -
 Potter and Whitfield - . - .
 Evans
 Braslow - - - - -

incompressible flow, the Potter and Whitfield criterion leads to values in agreement with the results of the Van Driest and Blumer formulas and also Braslow's curves, considering the fact that the advised value $R_{hh} = 900$ is a little too high near Mach 1 (the advised value below Mach 1 being 600). The difference between the roughness heights computed from these three criteria does not exceed .01 mm and remains smaller than the tolerance for the roughnesses used in industrial tests.

One must notice, however, that the very satisfying agreement thus obtained results from adopting the law $x^* = F(M)$ which defines the location of the roughnesses.

Thus if one used, for example, a constant value $x = 8$ mm, the differences would be doubled, increasing as the Mach number is raised. On the other hand, the use of the criterion R_{x^*} leads to relatively moderate values of R_{hh} , even up to Mach 3, and to x/h ratios varying very little with the Mach number.

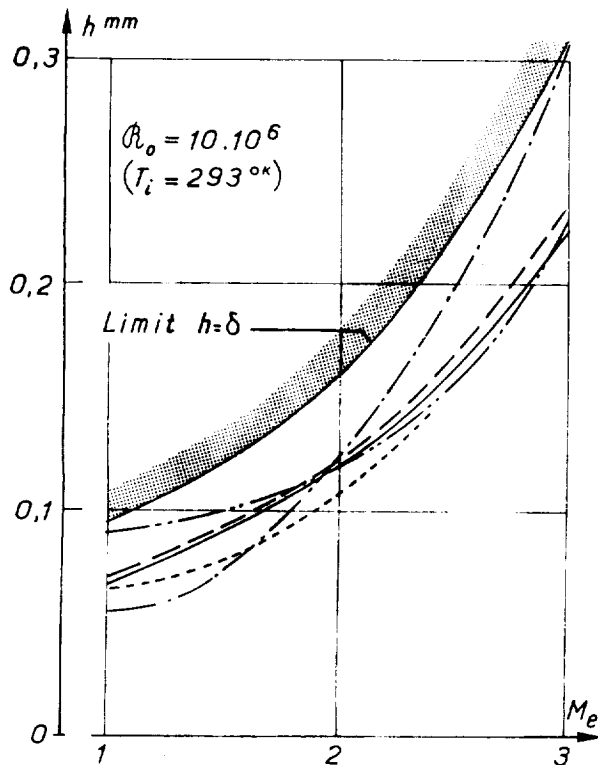


Fig. 8. Height of the Roughness h from: key same as Fig. 7.

obtained. In addition to the experiment in natural transition, the tests are made in artificially-initiated transition by spherical roughnesses arranged in a single line in three increments at a constant distance $x = 8$ mm; five roughness heights from 0.09 to 0.38 mm are studied.

The drag coefficient measured as a function of h and R_0 are plotted in Figs. 9a and 9b for $M = 1.65$ and 2.34 . At a Reynolds number $R_0 = 9.8 \cdot 10^6$ visualizations of the transition have been made for each height of roughness.* By using the results obtained for the location of the transition line [9] it is possible to determine the correction ΔC_{x_F} of the friction drag coefficient which must be introduced into the drag coefficients obtained in non-totally-initiated transition in order to bring the transition back on the line of the roughness (Figs. 9a and 9b).

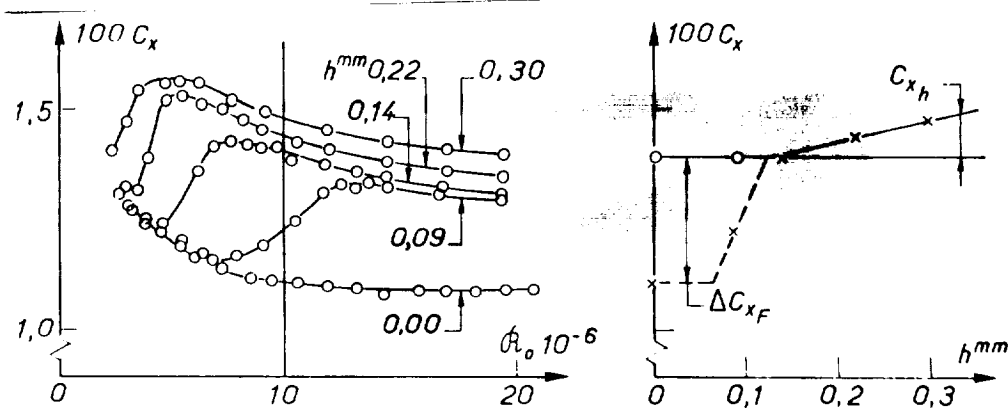
The additional drag coefficient C_{x_h} caused by the roughnesses of height h is then obtained by taking the point of zero height, after the correction ΔC_{x_F} ,

VIII. Additional Drag Caused by the Roughnesses

The criteria we have examined earlier in this article are sufficient to guide us in a study of initiation of transition. Nevertheless, in each particular case of wind tunnel and each type of model it is necessary to conduct some tests in order to determine the critical Reynolds roughness number to be adopted and the coefficients of additional drag coming from the roughness which permit an eventual corrective computation for industrial tests.

We present here such a test, done to specify the characteristics which can be applied to a given family of models in the supersonic channel of the Modane S-2 wind tunnel ($1.5 < M < 3$, $p_i \ll 2$ bars). The aircraft model with a symmetrically-profiled wing (Figs. 4, 5) has been studied with a zero angle of attack for the three Mach numbers 1.65, 2.03 and 2.34. In order to study only the wing and rudder surfaces, the transition is always initiated on the fuselage for all the Reynolds numbers

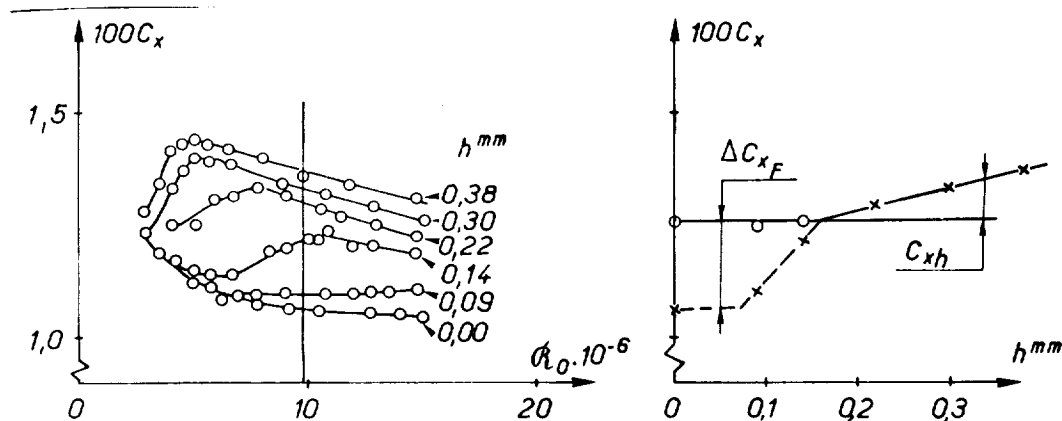
*The value of x^* corresponding to this Reynolds number is equal to 8 mm for the highest Mach number of the test: 2.34.



$M_e = 1.65$
 $x = 8 \text{ mm}$

$R_0 = 9.8 \cdot 10^6$

Fig. 9a. Before correction ΔC_{xF} ----
 After correction ΔC_{xF} —



$M_e = 2.34$
 $x = 8 \text{ mm}$

$R_0 = 9.8 \cdot 10^6$

Fig. 9b. Before correction ΔC_{xF} ----
 After correction ΔC_{xF} —

for origin of the drag coefficients, i.e. corresponding to a natural transition located in x .

One can draw the following conclusions, valid for the Mach range studied:

- The roughness height h sufficient to initiate the transition, under given conditions for M_e , R_0 and x , cannot be distinguished from that where the additional drag C_{xh} begins to be noticeable. In contrast to the transonic region [9], the notions of critical and limit roughness heights seem indissociable.
- For constant R_0 and x , the Reynolds roughness number varies little

with the Mach number. Its value corresponds to the results taken from the three criteria chosen in section VII as the following comparative table shows:

For $x = 8 \text{ mm}$, $R_0 = 9.8 \cdot 10^6$:

M_e	1.65	2.34	tests presented Braslow Van Driest-Blumer Potter-Whitfield
R_{hh}	850	1,050	
	900	900	
	770	900	
	850	1,050	

From the fact that the heights h vary essentially as $\sqrt{R_{hh}}$ it results that the differences between the values of the critical h obtained and those furnished by the three criteria mentioned above stay within the tolerances of the dimensions of the particles used in the test. /31

It therefore appears suitable to choose the easiest formula to use, i.e. that given by Van Driest and Blumer.

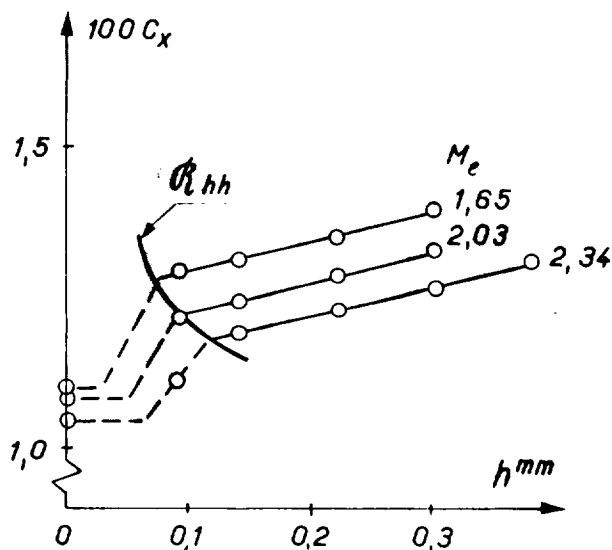


Fig. 10. $x = 8 \text{ mm}$, $p_i = 1.4 \text{ bar}$, $T_i = 300^\circ \text{ K}$.

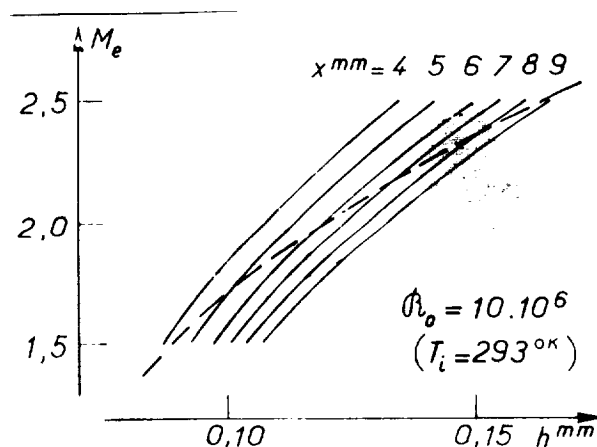


Fig. 11. Critical Heights According to Van Driest-Blumer —; curves $h = F(M_e)$ for $x = x^*$ ----.

- Beyond the critical roughness height, the increase of the additional drag coefficient C_{xh} is independent of the Reynolds number R_0 . It is practically independent of the Mach number (Fig. 10).

IX. Adaptation of the Roughness to an Industrial Test

M_e and R_0 are the parameters which appear in the definition of the location of the roughness line; x , M_e and R_0 are those which appear in the dimensioning of the spherical particles. In principle, it should thus be necessary to define an appropriate set of values for x and h for each condition of experiment. Thus, for a test which must be made between Mach 1.5 and 2.5 with a constant Reynolds number $R_0 = 10 \cdot 10^6$, the critical values of h are plotted in Fig. 11 as a function of M_e and x . In this figure the critical values of h corresponding to the values of x are also plotted as suggested in section V.

In practice, for industrial-type tests it is not possible to modify the parameters x and h for each test condition M_e , R_0 . It then becomes useful to know the error made on the measured drag coefficients when limited to the use of only one set of x and h values during the whole test. The error will always be minimized by choosing roughnesses which initiate the transition for the total anticipated program.

Several ways of conducting the test are possible:

- tests conducted with a constant Reynolds number. The values of x^* and h to be used are those computed with the highest Mach number of the test. In the case, for example, of a test conducted at $R_0 = 10 \cdot 10^6$ and $1.5 \leq M_e \leq 2.5$, Fig. 11 gives the values $x^* = 9$ mm, $h = 0.165$ mm. The correction on the drag which must be made, by definition equal to zero at $M_e = 2.5$, increases (Fig. 12) when M_e decreases, reaching the value $100 \Delta C_x = 0.029$ at $M_e = 1.5$ in the case of the model used for the tests discussed in this article. In relative value the correction reaches 2% of the real value of the drag coefficient. For a

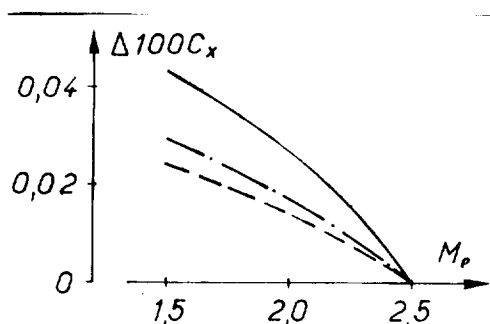


Fig. 12. $p_i = 1$ bar, $x = 9$ mm, $h = 0.165$ mm — — —; $R_0 = 10 \cdot 10^6$, $x = 9$ mm, $h = 0.165$ mm - - - -; $R_0 = 10 \cdot 10^6$, $x = 4$ mm, $h = 0.135$ mm - - -.

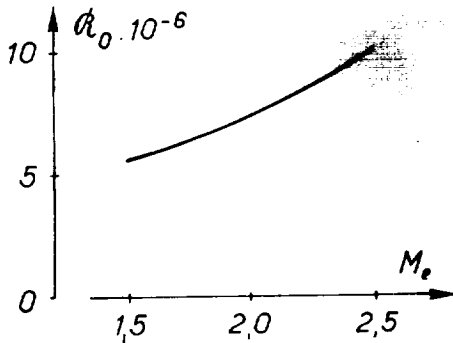
p_i are given in Fig. 12. They reach $100 \Delta C_x = 0.043$ at $M_e = 1.5$, that is 3% of the exact C_x , and are thus much greater than the corrections which must be made

location of the roughnesses upstream from the distance x^* , for example $x = 4$ mm, the height h would be 0.135 mm (Fig. 11) and the correction would reach $100 \Delta C_x = 0.024$ at Mach 1.5 (Fig. 12), i.e. 1.7% of the correct value of C_x . The small correction reduction obtained by choosing x smaller than x^* does not justify the use of roughnesses whose heights are close to the thickness of the boundary layer and then the use of small x/h ratios for which the formulas are not well known.

- experiments conducted at constant generating pressure p_i . Conserving the values $x^* = 9$ mm and $h = 0.165$ mm found earlier at $M_e = 2.5$ for $R_0 = 10 \cdot 10^6$ that is $p_i = 1$ bar, the corrections to be made on the drag when conducting a test at constant

on the results of tests conducted at constant Reynolds number.

- generating conditions which must be realized to avoid any correction. ^{/32}
If the variations of the Reynolds number have no determining effects on the test to be conducted, it is possible to give a low $R_0 = F(M_e)$ such that the height h always remains critical, whatever the Mach number. Indeed, if x and h have been determined for a Mach number M_{e0} and a Reynolds number R_{00} the Reynolds number to be realized in order not to introduce correction of additional drag C_{xh} to the test results corresponding to any Mach number is given by:



$$R_0 = R_{00} \left(\frac{1 + 0,2 M_e^2}{1 + 0,2 M_{e0}^2} \right)^{4/3}$$

The curve $R_0 = F(M_e)$ corresponding to the values x and h chosen for $M_{e0} = 2.5$ and $R_{00} = 10 \cdot 10^6$ is given in Fig. 13. The corresponding generating pressures will vary from 1 bar for $M_e = 2.5$ to 0.38 bar for $M_e = 1.5$.

X. Conclusion

Relatively simple formulas permit defining the location and the critical height of the rough particles, i.e. the height sufficient to initiate the transition artificially without any drag increase.

Fig. 13. $\Delta C_x = 0$.

The preliminary study made in the Modane S 2 wind tunnel shows that between Mach 1 and 3 the criterion proposed by Van Driest is the best adapted to define the height of spherical roughnesses arranged in a single row. However, the results reported in this article can only be applied to a family of wings with the same sweep and must not be used for other cases.

The higher the Mach number, in supersonic flow, the less valid are the conditions for transition initiation for neighboring Mach or Reynolds numbers. In industrial tests the generating conditions are defined from the desired accuracy to avoid any modification in the locations and heights of the critical roughnesses. In a case where great accuracy is required, to obtain an accurate result for the total drag the program of the test will be divided into small ranges of Mach and Reynolds numbers, so that the corrective terms C_{xh} stay lower than a tolerable value.

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